

Selected B Results

From the other B factory

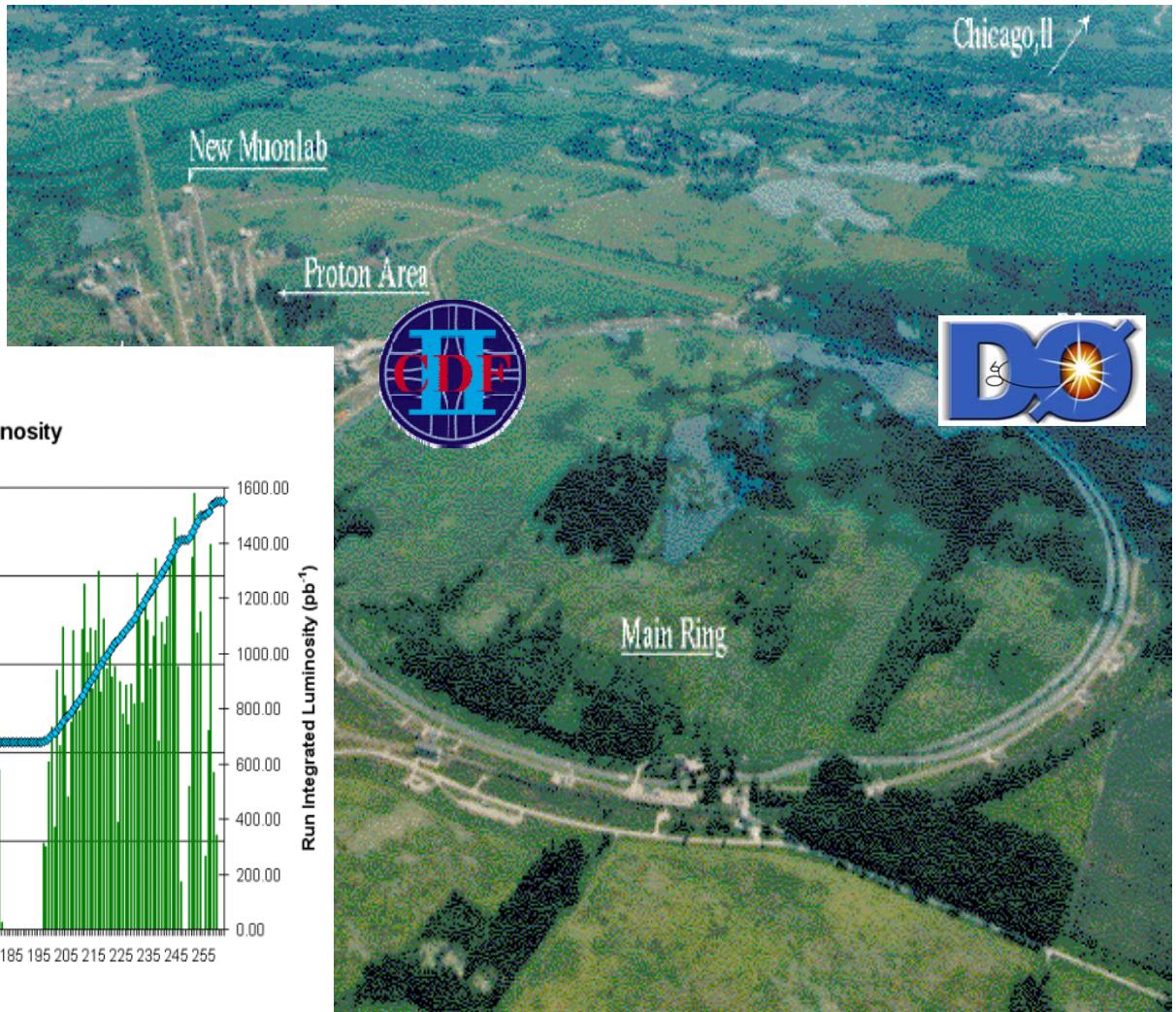
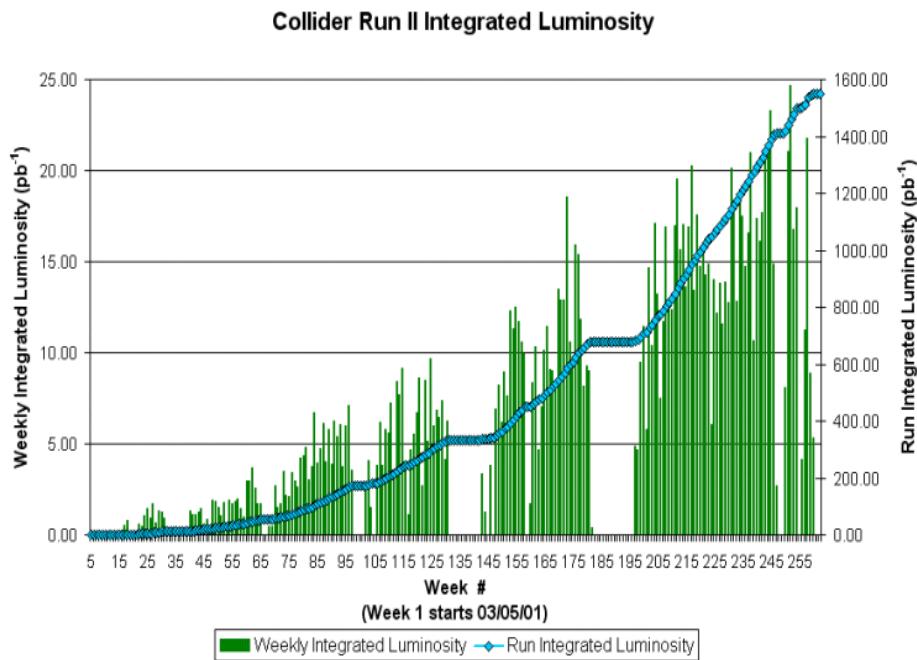


- Collider and Detectors
- B hadron spectroscopies
 - Λ_b lifetime
 - $Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$
 - B^{**} , B_{s2}^*
 - B_c mass
- FCNC rare decays
 - $B_d^0, B_s^0 \rightarrow \mu^+ \mu^-$
 - $B_s^0 \rightarrow \mu^+ \mu^- \phi$
 - $D^+ \rightarrow \mu^+ \mu^- \pi^+$
- Bs mixing and lifetimes
 - lifetime difference $\Delta\Gamma_s$
 - oscillation frequency Δm_s

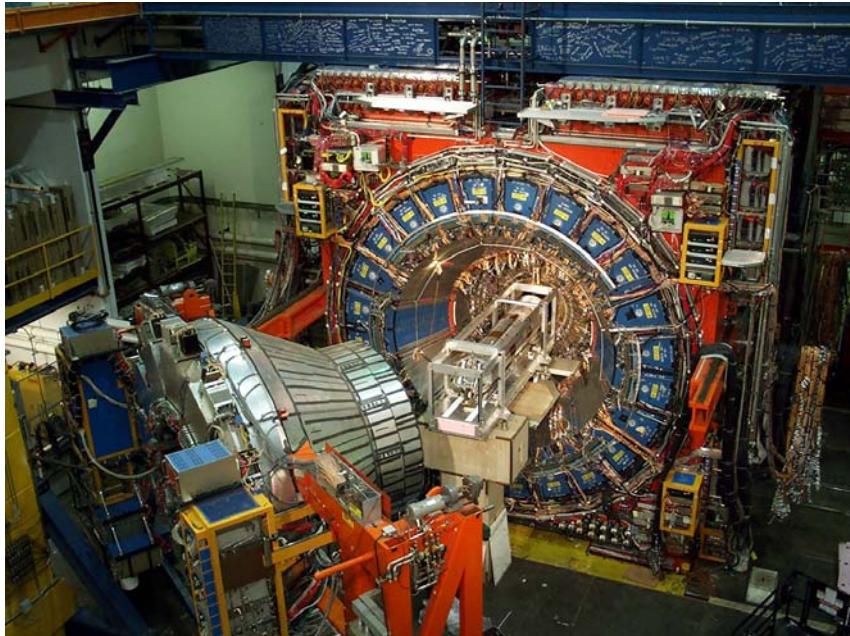
On behalf of CDF and DØ Collaboration

Tevatron Collider

- integrated luminosity delivered:
 $\sim 1.6 \text{ fb}^{-1}$
per experiment
- record instantaneous luminosity:
 $1.7 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



The Detectors



DØ:

recorded 1.2 fb^{-1}

B physics capability:
a magnetic compact tracker,
large muon coverage, ...

CDF:

Recorded 1.4 fb^{-1}

B physics capability:
large tracking volume,
vertex trigger,
large tracker,
particle ID,
large trigger bandwidth ...



B Production @ Tevatron

Good: Larger b cross section
 $\sim 100 \mu\text{b} \rightarrow 10\text{kHz}$ real b's

Bad: even larger cross section
from QCD backgrounds
 $\sim 50 \text{ mb} !$

Keys:

Trigger to select b candidates

CDF: μ , secondary vertex;
DØ: μ only

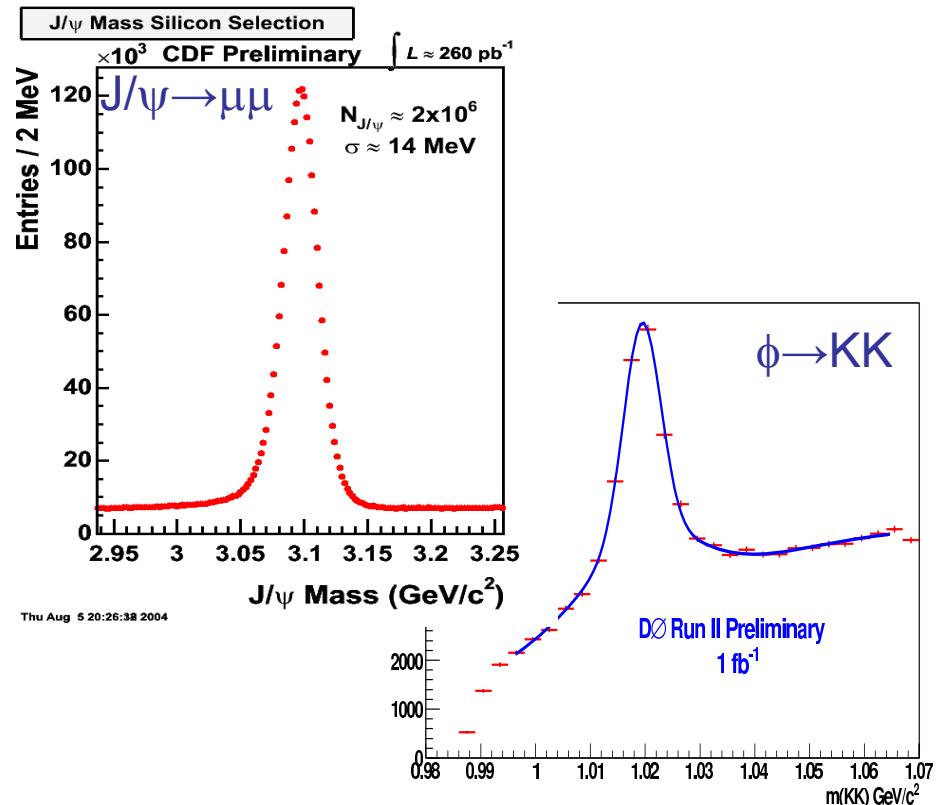
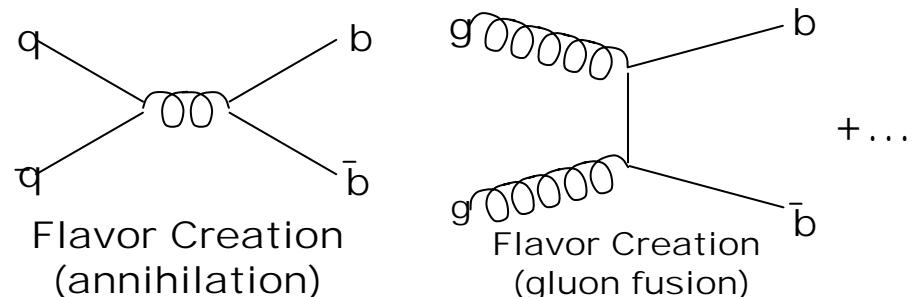
Large bandwidth to record them

CDF: ~ 100 Hz to tape

DØ: 50 Hz

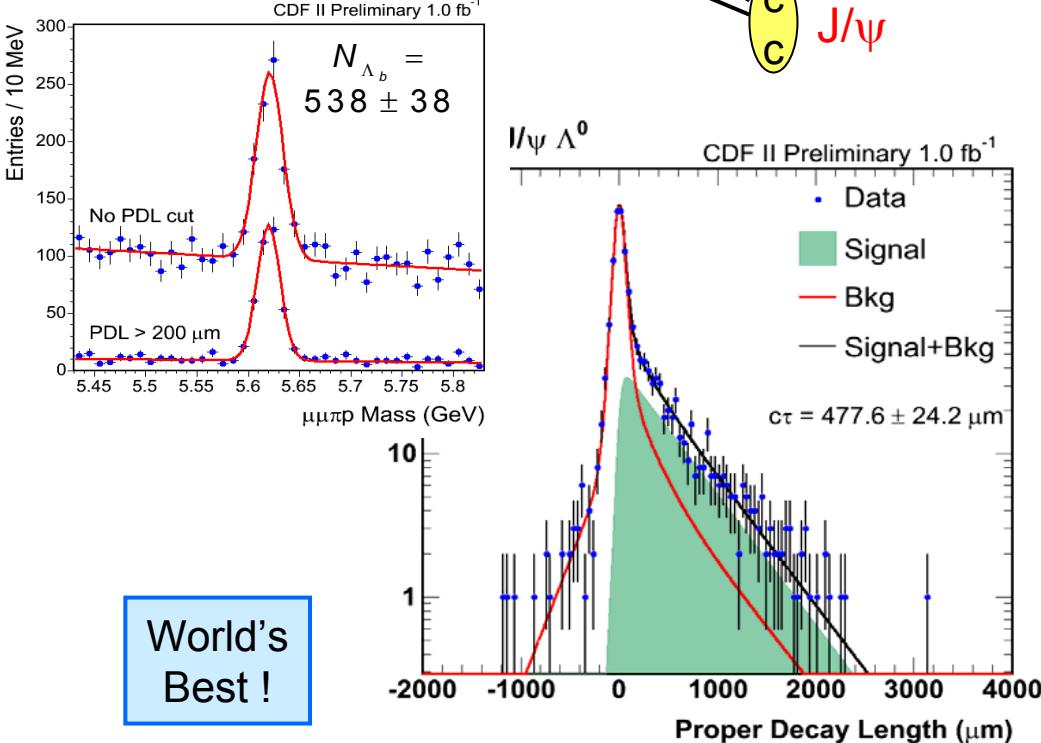
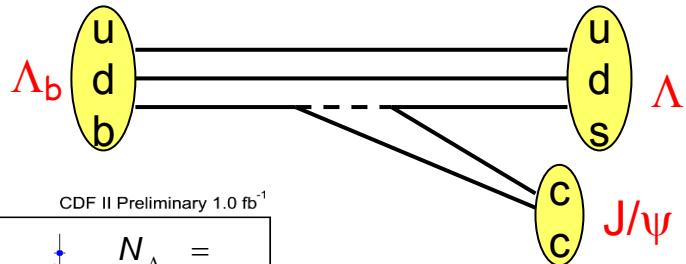
All kind of B hadrons are
produced: B_d , B_s , B_c , B^{**} , Λ_b , Ξ_b , ...

- B^+ , B : ~80%
- B_s , b-baryon: ~10%
- B_c : ~0.05%



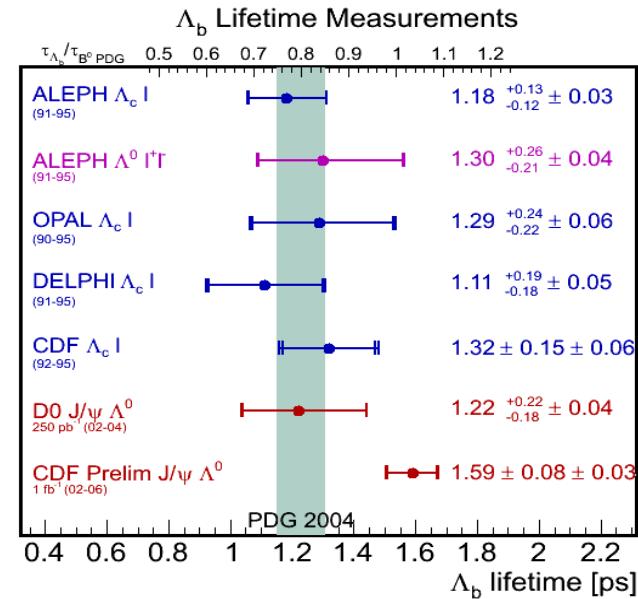
Λ_b Lifetime

A (udb) baryon, the lightest with a b-quark



Full $\Lambda_b \rightarrow J/\psi \Lambda$ reconstruction
with $J/\psi \rightarrow \mu\mu$ and $\Lambda \rightarrow p\pi$

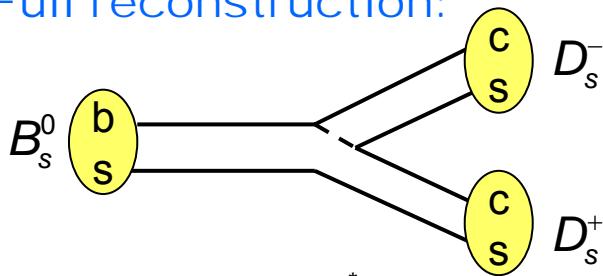
$B_d \rightarrow J/\psi(\mu\mu) K_s(\pi\pi)$ for
cross checks



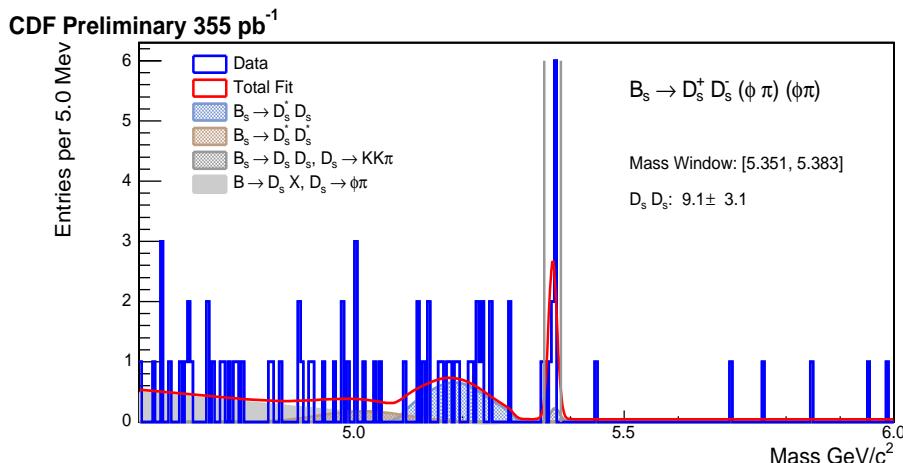
The new measurement appears to be
“interestingly” above the previous
world average. Time will tell...

$$Br(B_s^0 \rightarrow D_s^+ D_s^-)$$

Full reconstruction:



with $D_s \rightarrow \phi\pi, KK^*, \pi\pi\pi$

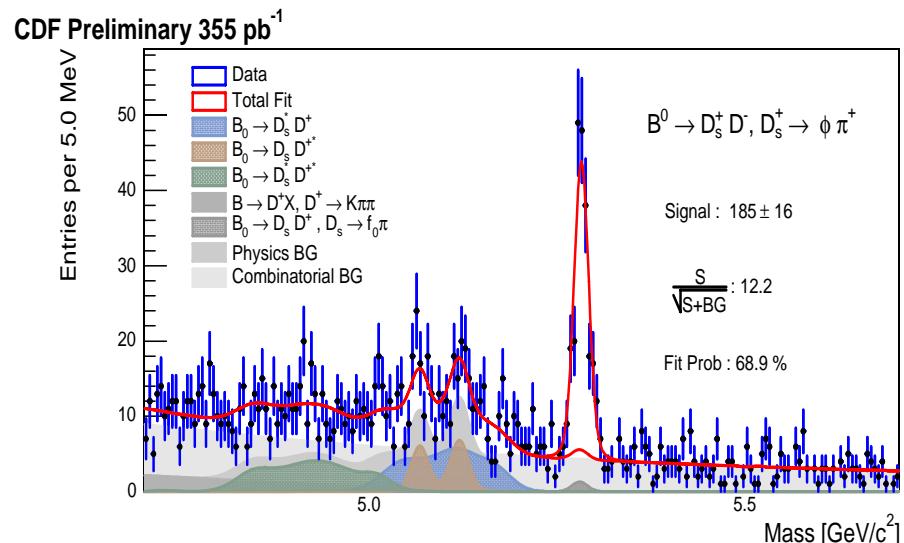


23.5 ± 5.5 total candidates

First observation of this fully reconstructed decay mode

Normalization:

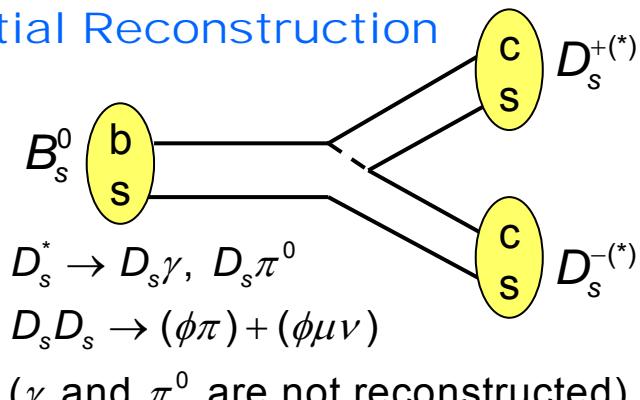
$$B^0 \rightarrow D_s(\phi\pi, KK^*, \pi\pi\pi) + D(K\pi\pi)$$



$$\frac{Br(B_s^0 \rightarrow D_s^+ D_s^-)}{Br(B^0 \rightarrow D_s^+ D_s^-)} = 1.67 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}) \pm 0.24(f_s/f_d) \pm 0.39(Br_{\phi\pi})$$

$$Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$$

Partial Reconstruction



Inclusive $D_s D_s$, $D_s D_s^*$, $D_s^* D_s^*$ analysis

Normalization

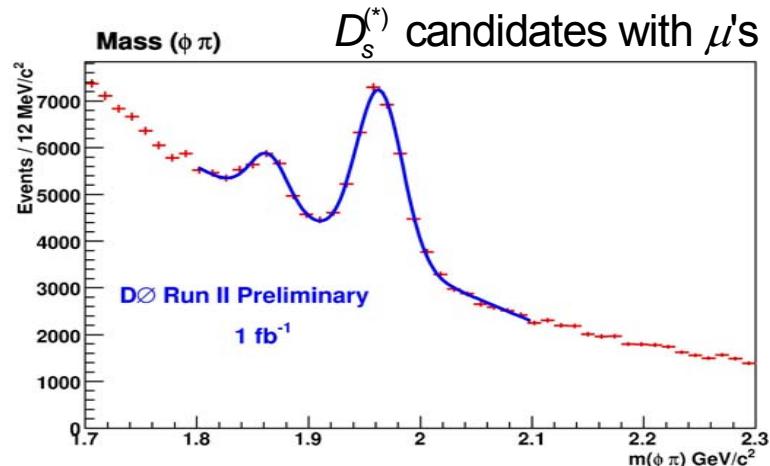
$$B_s^0 \rightarrow D_s^{(*)} + \mu\nu \rightarrow \phi\pi + \mu\nu$$

Measure the relative rate

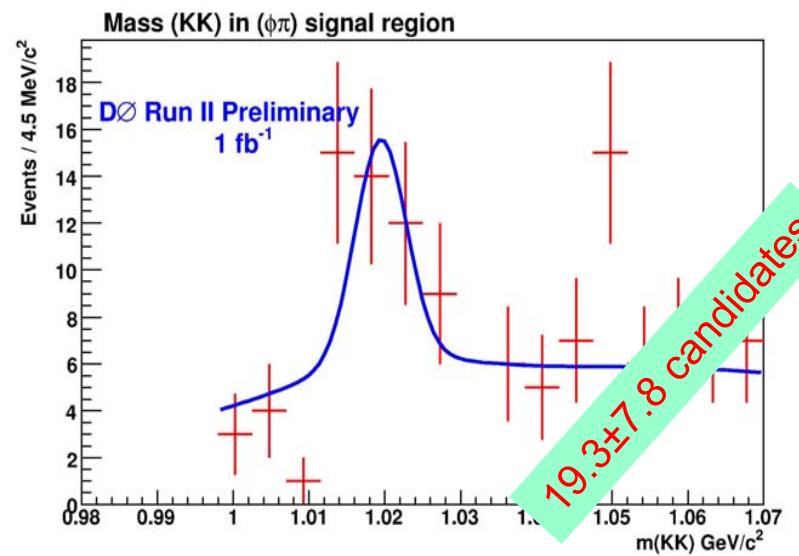
$$R = \frac{Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) \cdot Br(D_s \rightarrow \phi\mu\nu)}{Br(B_s^0 \rightarrow D_s^{(*)} \mu\nu)}$$

$$Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.071 \pm 0.032(\text{stat})^{+0.029}_{-0.025}(\text{syst})$$

Since $D_s^{(*)} D_s^{(*)}$ is a CP eigenstate, this decay mode can be used to measure $\Delta\Gamma_{\text{CP}}$.



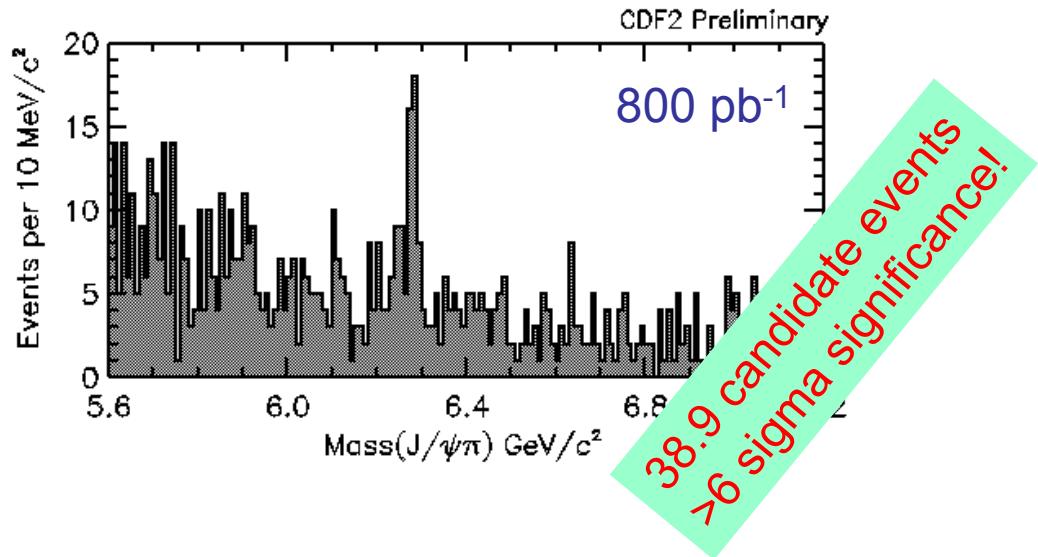
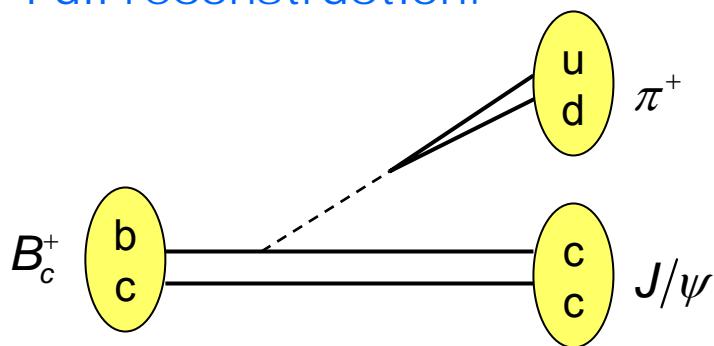
search for another ϕ ...



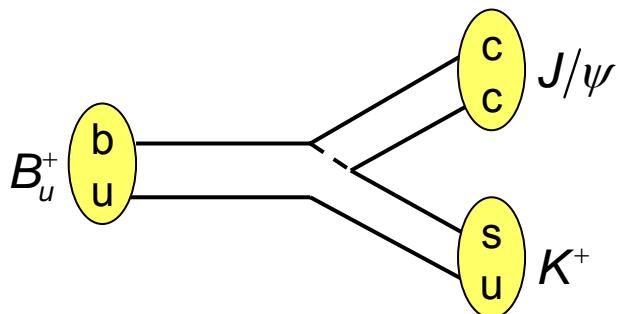
B_c Mass

A (bc) bound state, unique (qq) system with two heavy quarks
Not produced at B factories, rarely produced at Tevatron

Full reconstruction:



$B_u \rightarrow J/\psi K$ as benchmark



B_c mass =
 $6275.2 \pm 4.3(\text{stat}) \pm 2.3(\text{syst}) \text{ MeV}/c^2$

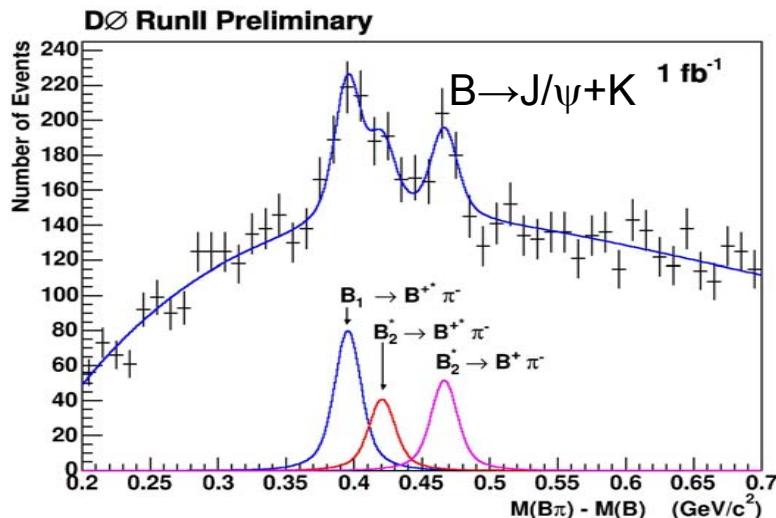
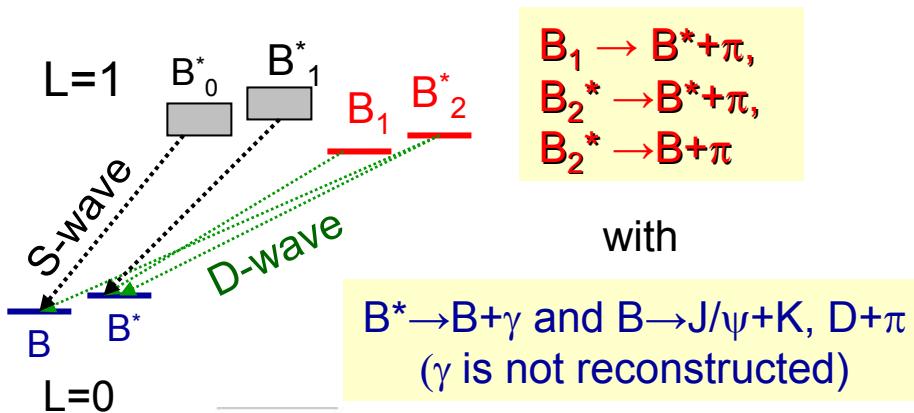
World's Best!

Lattice QCD calculation
 $M(B_c) = 6304 \pm 12^{+18}_{-0} \text{ MeV}/c^2$

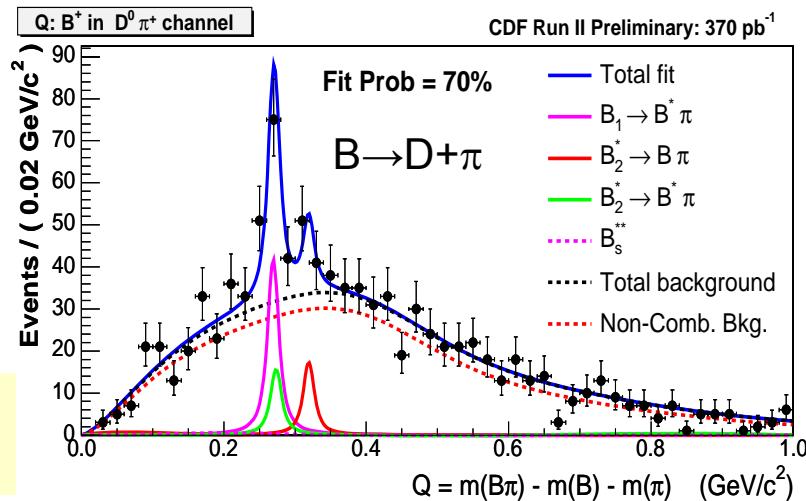
(Allison et al, PRL 94, 172001 (2005))

B_J^{*} (B^{**}) Mesons

Four L=1 states of (bd) system
 two broad (~100 MeV) and
 two narrow (~10 MeV) resonances



Identification of narrow resonances



CDF

$$M(B_1) = 5734 \pm 3 \pm 2 \text{ MeV}/c^2$$

$$M(B_2^*) = 5738 \pm 5 \pm 1 \text{ MeV}/c^2$$

D0

$$M(B_1) = 5720.8 \pm 2.5 \pm 5.3 \text{ MeV}/c^2$$

$$M(B_2^*) - M(B_1) = 25.2 \pm 3.0 \pm 1.1 \text{ MeV}/c^2$$

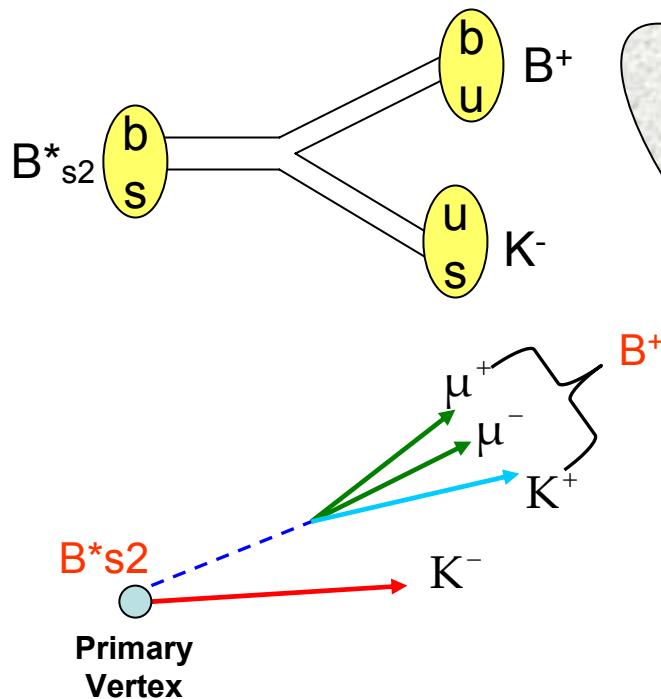
$$\Gamma(B_2^*) = \Gamma(B_1) = 6.6 \pm 5.3 \pm 4.2 \text{ MeV}$$

B_{s2}^* Meson

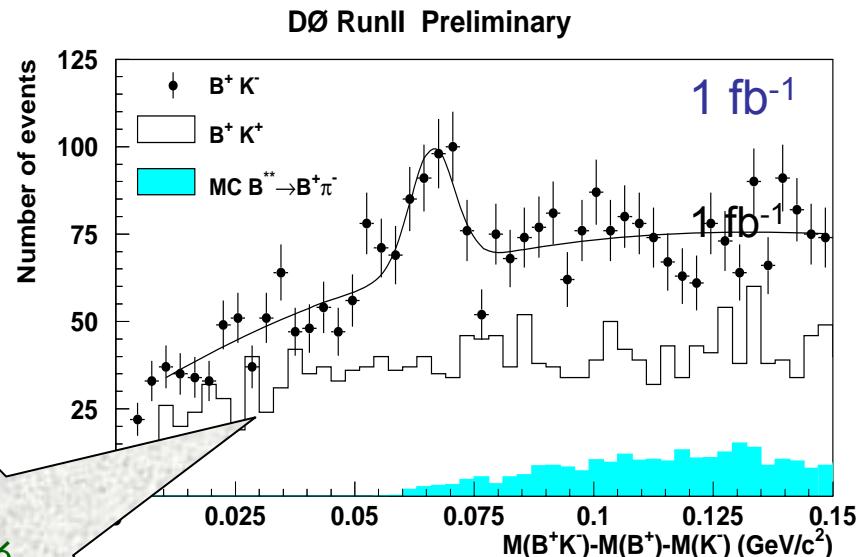
Similar to B^{**} states, the quark model predicts 4 P-states for (bs) system. B_{s2}^* is the counterpart of B_{s2}^* .

Full Reconstruction

$$B_{s2}^* \rightarrow B^+ + K^- \text{ with } B^+ \rightarrow J/\psi + K^+$$



Mass difference: $M(B^+K^-) - M(B^+) - M(K^-)$



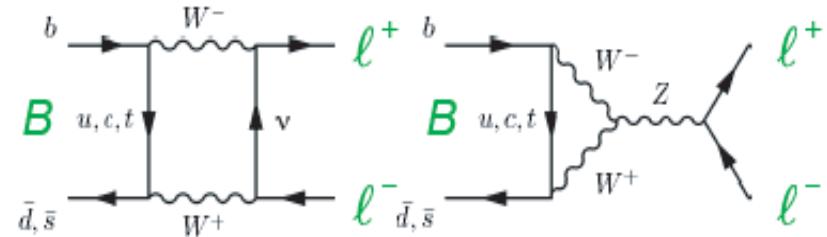
$$M(B_{s2}^*) = 5839.1 \pm 1.4 \pm 1.5 \text{ MeV}$$

135±31 candidates

First direct observation
with 5 sigma !

FCNC Rare Decays

The flavor changing neutral current interaction is forbidden at tree-level in SM, but can occur through loop diagrams such as those at the right

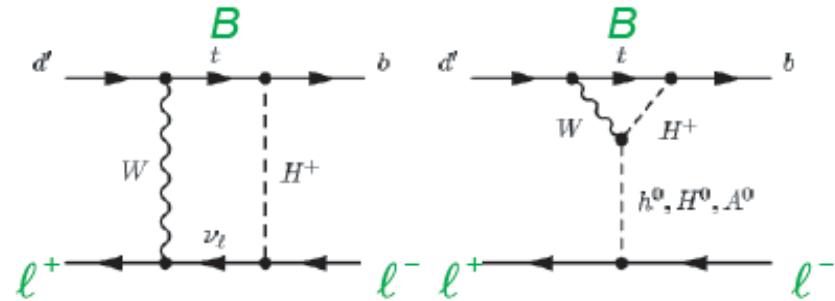


However, the rate is further suppressed by helicity conservation for light leptons. The estimated rate are

$$Br(B_s^0 \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.5) \times 10^{-9}$$

$Br(B_d^0 \rightarrow \mu^+ \mu^-)$ is further suppressed by factor of $|V_{td}/V_{ts}|^2 \approx 0.04$.

In MSSM, additional contributions are expected, the branching ratio is expected to grow as $\tan^4 \beta$ or $\tan^6 \beta$, ideal for probing indirect probing of new physics



$$B_d^0, B_s^0 \rightarrow \mu^+ \mu^-$$

Large continuum $\mu\mu$ background

Drell-Yan

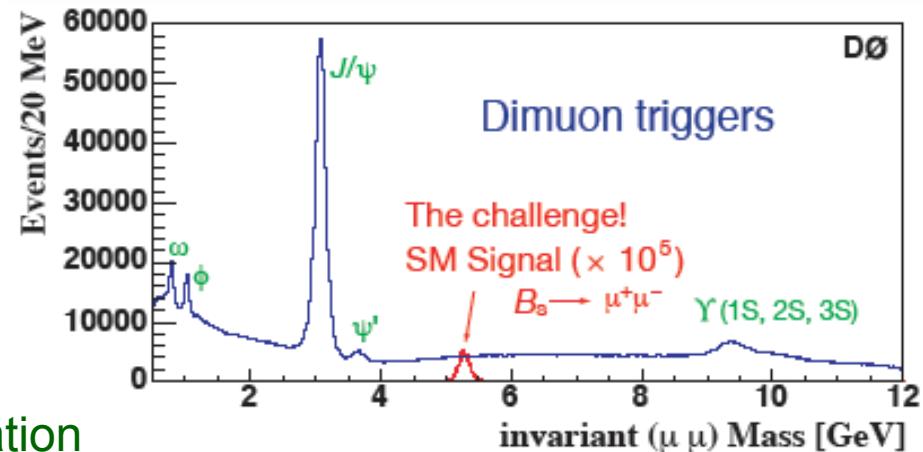
semileptonic decays

e.g. $b \rightarrow \mu c X$, $c \rightarrow \mu X$

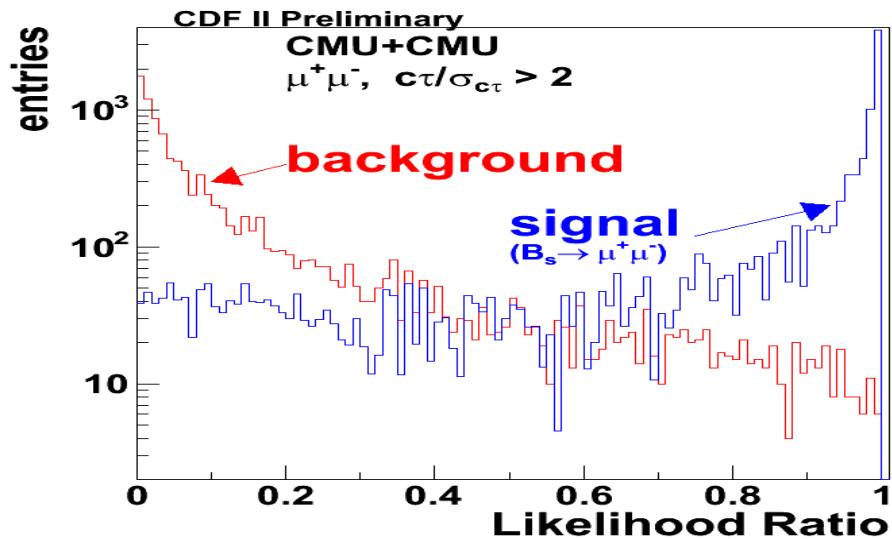
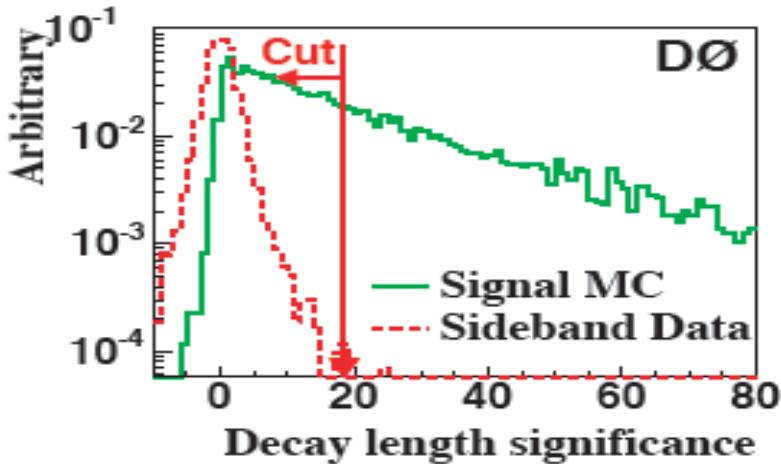
fakes

Exploit kinematics

decay length, pointing angle, isolation



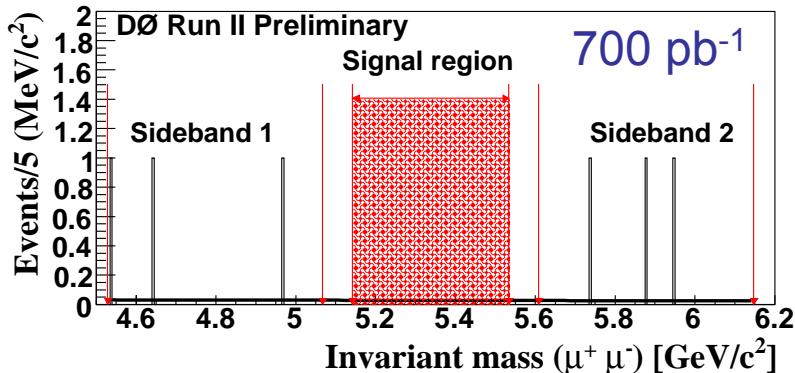
DØ cuts on these variables directly while CDF cuts on the likelihood



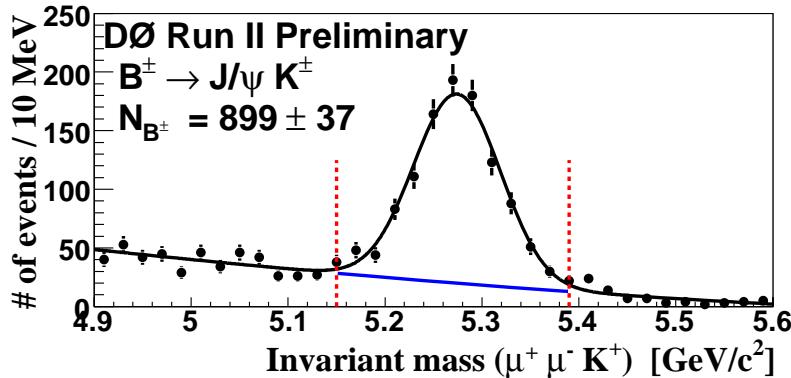
Both experiments pursue blind analysis

$$B_d^0, B_s^0 \rightarrow \mu^+ \mu^-$$

Sidebands to model backgrounds



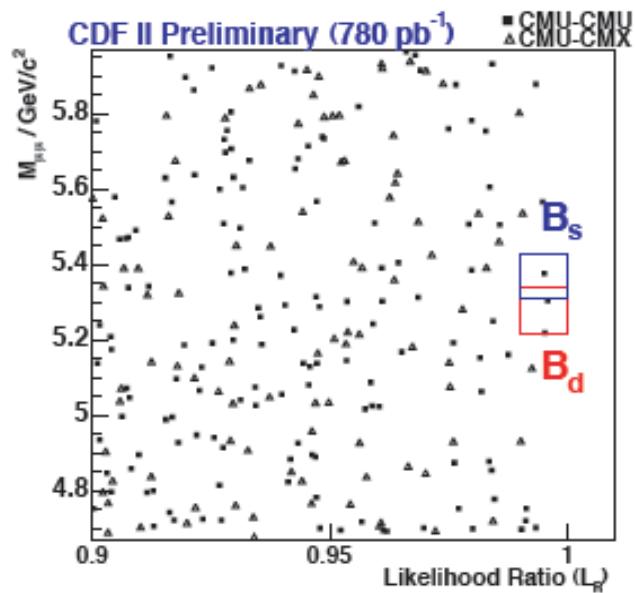
$B^\pm \rightarrow J/\psi K^\pm$ for normalization



(DØ does not have the mass resolution to separate B_d and B_s states)

DØ sensitivity @ 95% CL

$$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 2.3 \times 10^{-7}$$



CDF: (actual limit @ 95% CL)

$$Br(B_d^0 \rightarrow \mu^+ \mu^-) < 3.0 \times 10^{-8}$$

$$Br(B_s^0 \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-7}$$

about a factor of 50 away from the standard model expectation

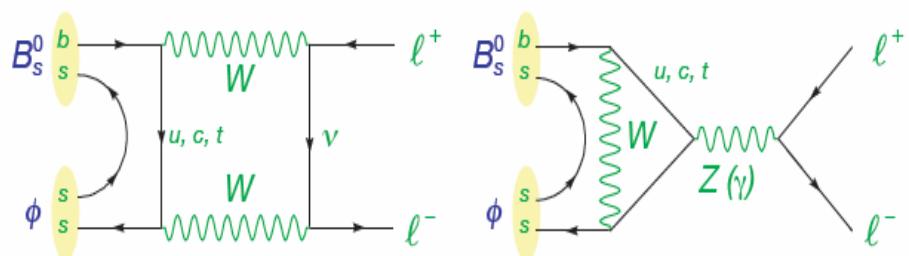
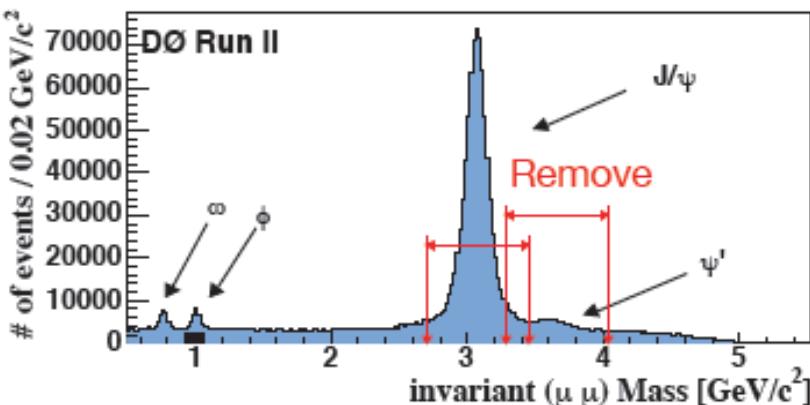
$$B_s^0 \rightarrow \mu^+ \mu^- \phi$$

Expected from loop diagrams in the standard model. Estimated rate: $Br(B_s^0 \rightarrow \phi \mu^+ \mu^-) \sim 1.6 \times 10^{-6}$

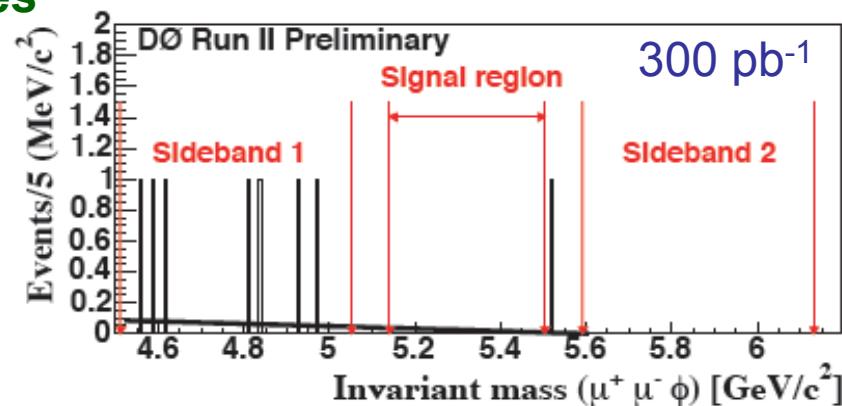
Potential enhancement from new physics.

Use the same discrimination variables as the $B_s \rightarrow \mu^+ \mu^-$ analysis.

Remove events with $\mu\mu$ from J/ψ and ψ' resonances



No events observed in the signal region, using side band to estimate backgrounds



$$Br(B_s^0 \rightarrow \mu^+ \mu^- \phi) < 4.1 \times 10^{-6} @ 95\% CL$$

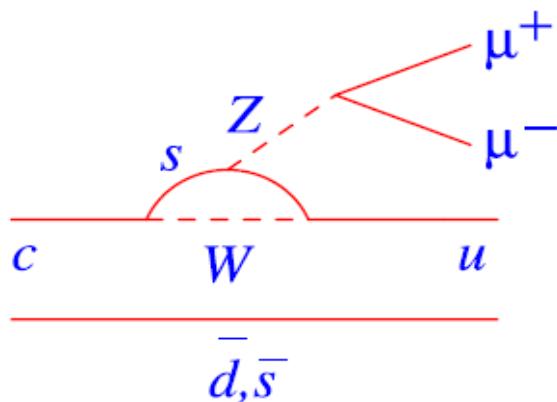
Only a factor of 3 away from the SM value!

$$D^+ \rightarrow \mu^+ \mu^- \pi^+$$

Strict experimental limits on FCNC transitions for down-type quarks
 $b \rightarrow s, s \rightarrow d$

relatively weak limit on FCNC transition involving up-type quarks

$D^+ \rightarrow \mu^+ \mu^- \pi^+$ decay is expected from FCNC $c \rightarrow u$ transition



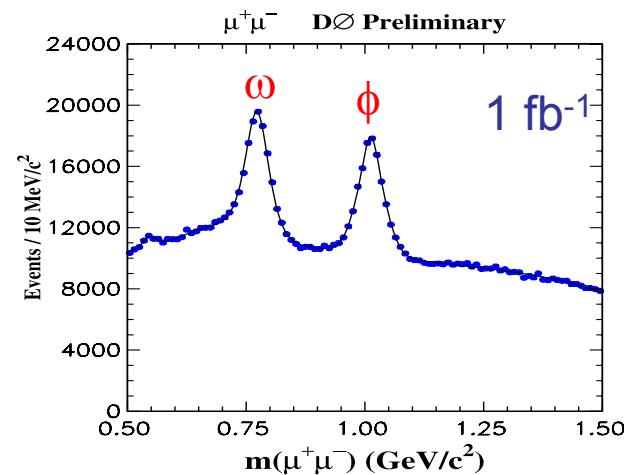
with small $Br \sim 10^{-8} \dots$

But enhancement is expected from physics beyond standard model

Background from resonance production:

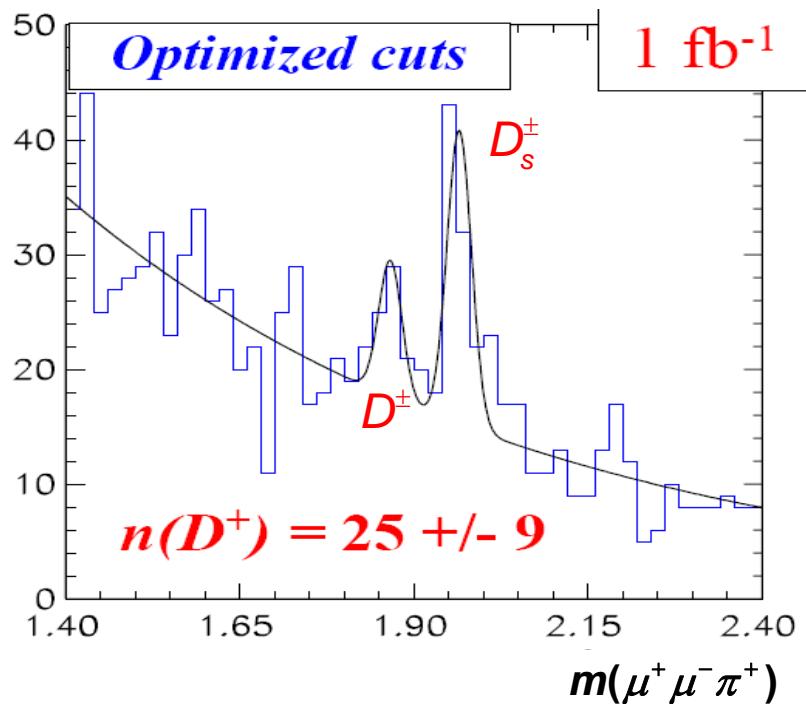
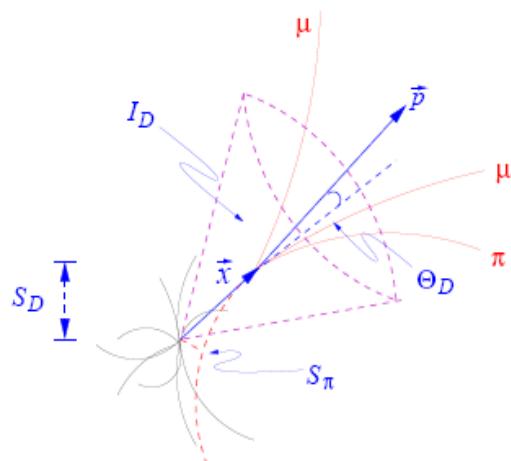
$$D_s^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+,$$

$$D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$$



However
 $m_{\mu\mu} \neq m_\phi$ for $c \rightarrow u$ transition!

$$D^+ \rightarrow \mu^+ \mu^- \pi^+$$



- $D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+ \mu^- \pi^+$ (**resonance**):
 $0.96 \leq m_{\mu\mu} \leq 1.06 \text{ GeV}/c^2$

Normalize to

$$D_s^+ \rightarrow \phi\pi^+ \rightarrow \mu^+ \mu^- \pi^+$$

$$\begin{aligned} Br(D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+ \mu^- \pi^+) \\ = (1.75 \pm 0.70 \pm 0.50) \times 10^{-6} \end{aligned}$$

CLEO: $(2.7^{+3.6}_{-1.8} \pm 0.2) \times 10^{-6}$

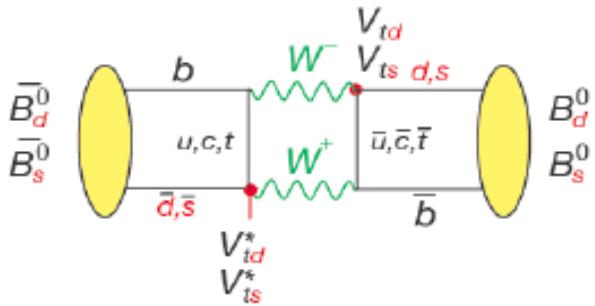
- $D^+ \rightarrow \mu^+ \mu^- \pi^+$ (**continuum**):
 $m_{\mu\mu} \leq 0.96 \text{ or } m_{\mu\mu} \geq 1.06 \text{ GeV}/c^2$

17 events observed
with 20.9 ± 3.4 expected

$$\begin{aligned} Br(D^+ \rightarrow \mu^+ \mu^- \pi^+) \\ < 4.7 \times 10^{-6} @ 90\% \text{ CL} \end{aligned}$$

B_s^0 Mixing & Decays

The box diagram like the one below and common decay modes of B_s^0 and \bar{B}_s^0 such as $B_s^0, \bar{B}_s^0 \rightarrow J/\psi \phi$ lead to mass matrix



$$i \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

↓

The two mass eigenstates have small differences in mass and decay width

$$\Delta m_s = M_H - M_L = 2|M_{12}|$$

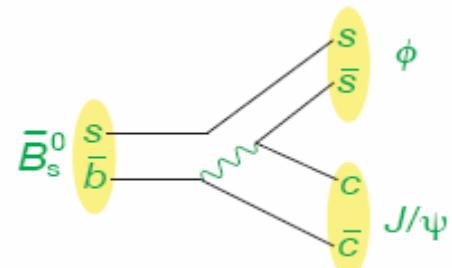
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos\varphi$$

$\varphi = 0.3^\circ$ in SM \Rightarrow mass and CP eigenstates are largely identical

$\Delta\Gamma_s$ can be measured by studying $B_s^0, \bar{B}_s^0 \rightarrow J/\psi \phi$ decays since both $|B_H\rangle$ and $|B_L\rangle$ are involved in the decay

$$B_s^0 \rightarrow J/\psi \phi$$

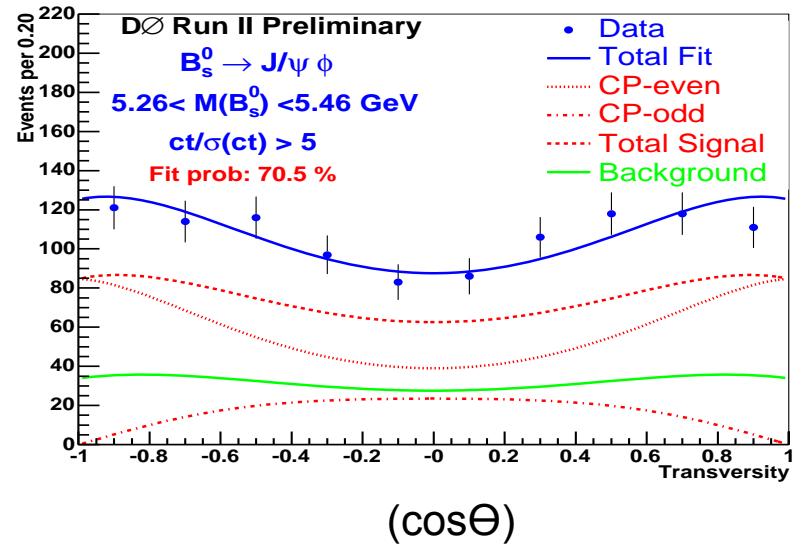
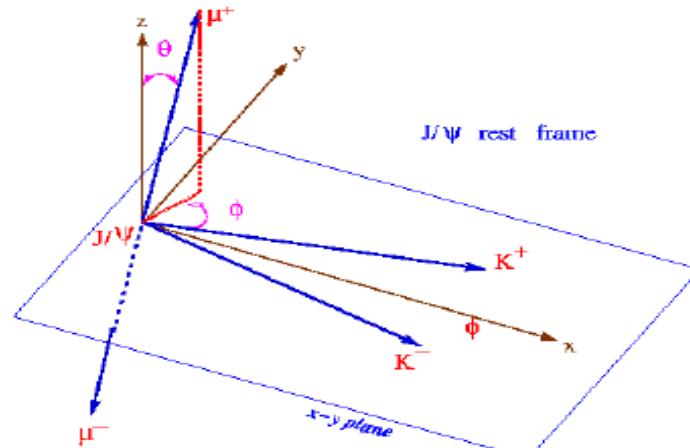
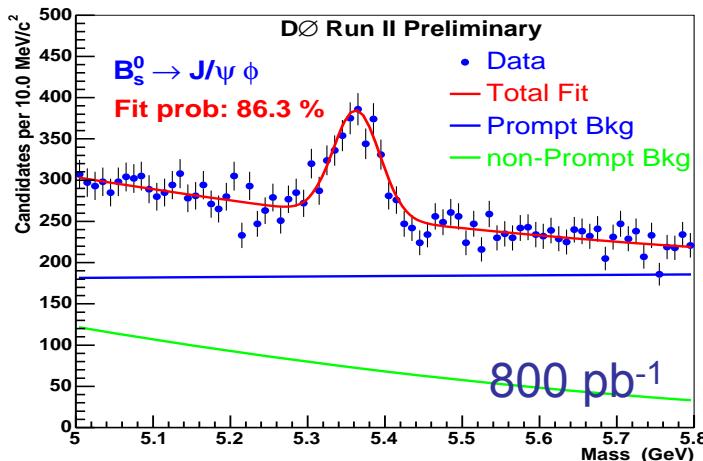
$$\bar{B}_s^0 \rightarrow J/\psi \phi$$



B_s Lifetime Difference

Full B_s → J/ψ ϕ Reconstruction

$$J/\psi \rightarrow \mu^+ \mu^- \text{ and } \phi \rightarrow K^+ K^-$$

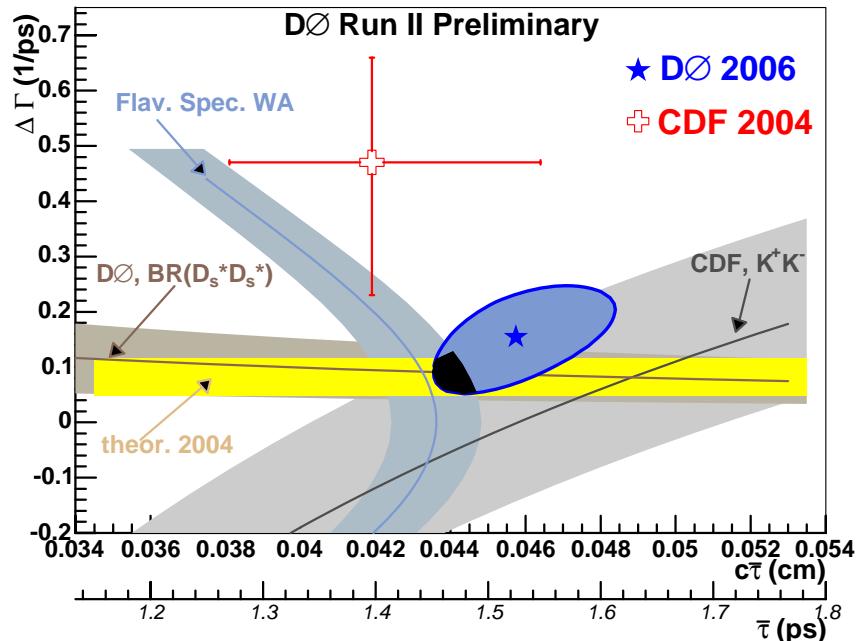
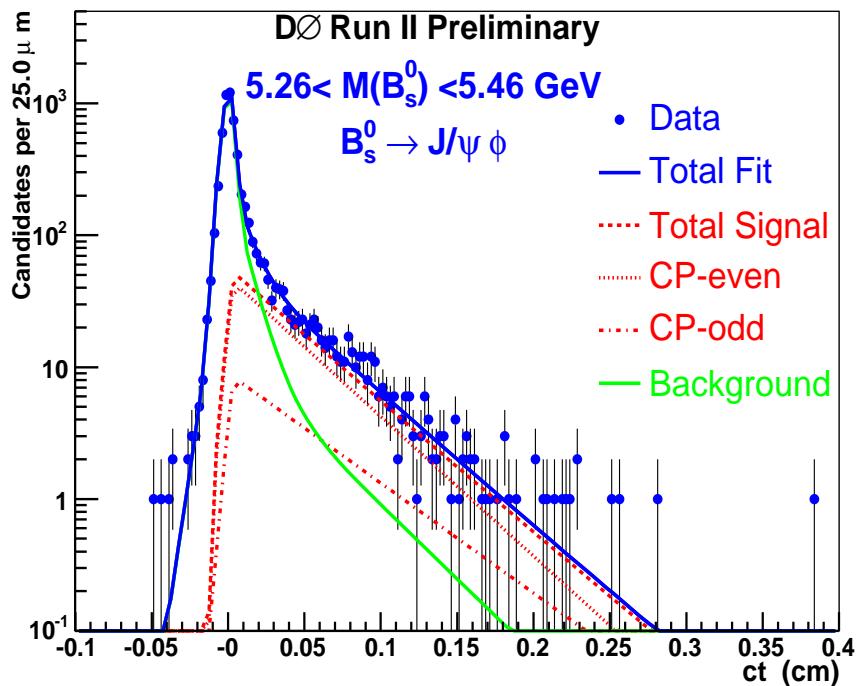


CP-even and CP-odd components are expected to have different angular distributions of the decay particles

Simultaneous fits to distributions of angles and the decay length to extract lifetimes of the two mass (and CP) eigenstates

B_s Lifetime Difference

Different lifetimes for the two mass eigenstates in the decay length fit



$$\bar{\tau}_{B_s} = \frac{\tau_H + \tau_L}{2} = 1.53 \pm 0.08^{+0.01}_{-0.03} \text{ ps}$$

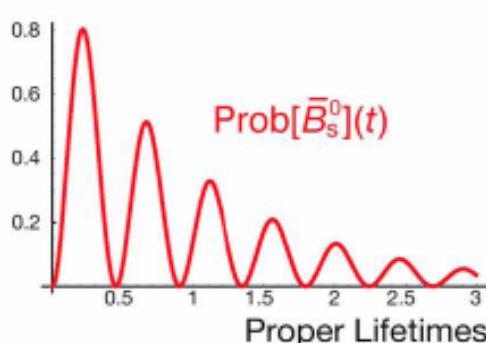
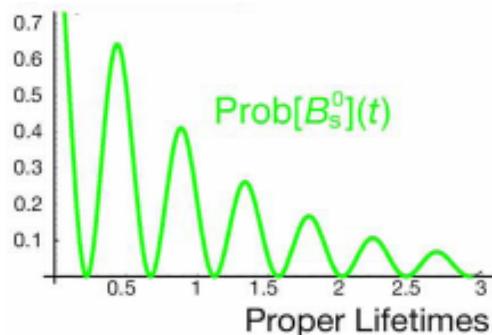
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.15 \pm 0.10^{+0.03}_{-0.04} \text{ ps}^{-1}$$

B_s^0 Oscillations

For an initial B_s^0

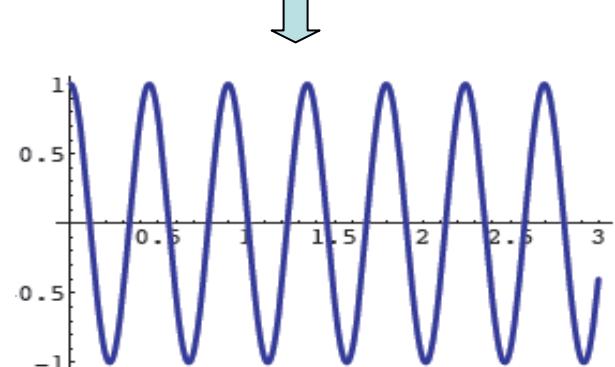
$$\text{Prob}(B_s^0 \rightarrow B_s^0)(t) = \frac{1}{4} (e^{-\Gamma_H t} + e^{-\Gamma_L t} + 2e^{-\Gamma t} \cos(\Delta m_s t))$$

$$\text{Prob}(B_s^0 \rightarrow \bar{B}_s^0)(t) = \frac{1}{4} (e^{-\Gamma_H t} + e^{-\Gamma_L t} - 2e^{-\Gamma t} \cos(\Delta m_s t))$$



Asymmetry:

$$A = \frac{N(B_s^0) - N(\bar{B}_s^0)}{N(B_s^0) + N(\bar{B}_s^0)} \propto \cos(\Delta m_s t)$$

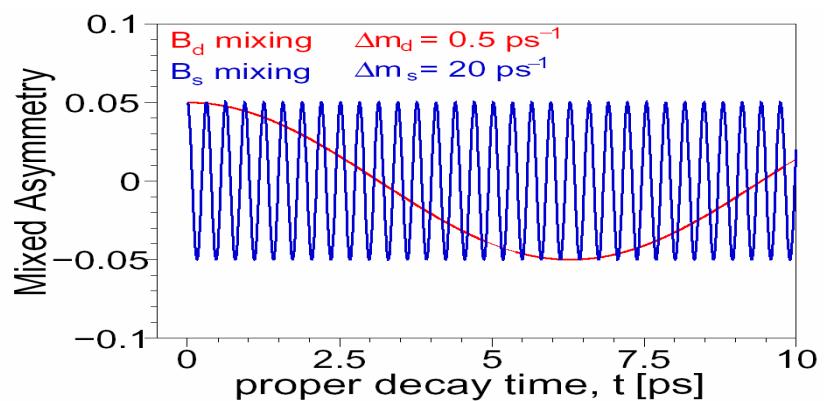


Compared with B_d^0 oscillation:

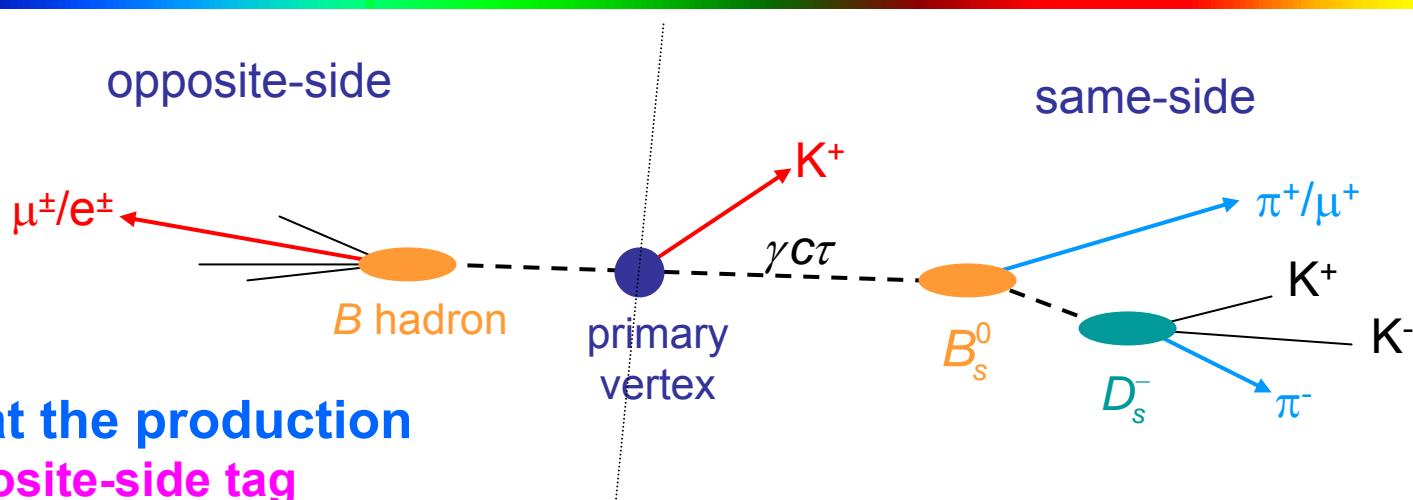
$$\Delta m_s \propto |V_{tb}^* V_{ts}|^2 \sim >> \Delta m_d \propto |V_{tb}^* V_{td}|^2$$

B_s^0 oscillates much fast!

World Average Limit
 $\Delta m_s > 14.4 \text{ ps}^{-1}$



Analysis Technique



Flavor at the production

- opposite-side tag
 - lepton from the other b decay
 - jet charge
 - (CDF: $\varepsilon D^2 = 1.5\%$, DØ: $\varepsilon D^2 = 2.5\%$)
- same-side tag
 - kaon from fragmentation
 - (CDF: $\varepsilon D^2 \sim 3.5\%, 4.0\%$)

Tagging power: εD^2

- ε is tagging efficiency
- $D = 1 - 2w$: dilution
- w: wrong tag probability

- ## Decay proper time
- decay length (vertices)
 - boost correction (momentum)

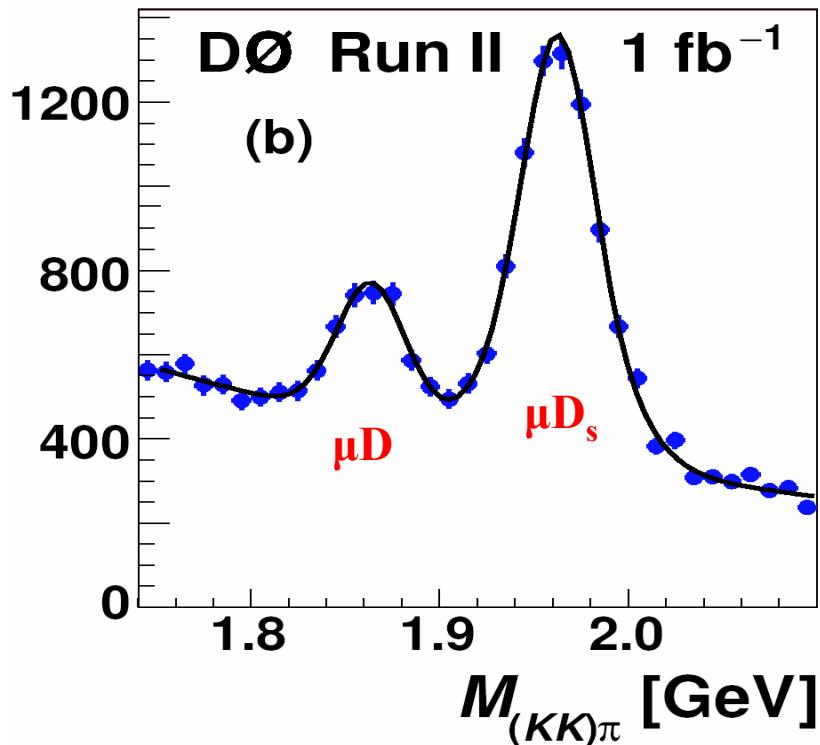
Flavor at the decay

- Full reconstruction:
 $B_s^0 \rightarrow \pi^+ D_s^-$ ($\sigma_{c\tau} \sim 90$ fs)
- Partial reconstruction:
 $B_s^0 \rightarrow \ell^+ \nu D_s^-$ ($\sigma_{c\tau} \sim 150$ fs)

B_s^0 Reconstruction

DØ: semileptonic B_s decay only

$$B_s^0 \rightarrow \mu^+ D_s^- + X \rightarrow \mu^+ \phi \pi^- + X$$



5,600 tagged μD_s events

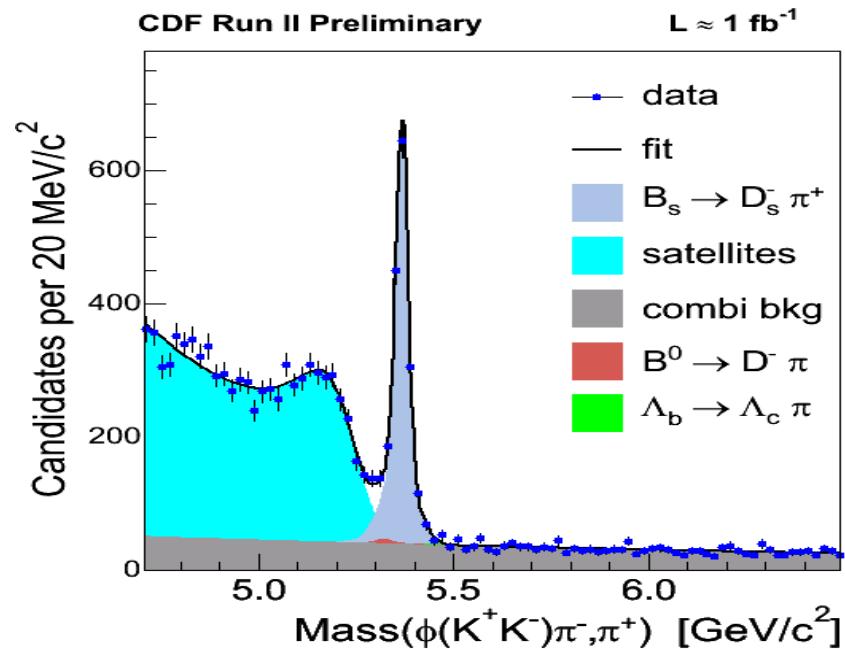
~20% tagging efficiency

~85% μD_s events are “signal”

CDF: B_s in both semileptonic and hadronic decays

$$B_s^0 \rightarrow \pi^+ D_s^-; B_s^0 \rightarrow \ell^+ \nu D_s^-; \dots$$

with $D_s \rightarrow \phi \pi, K^* K, \pi \pi \pi$

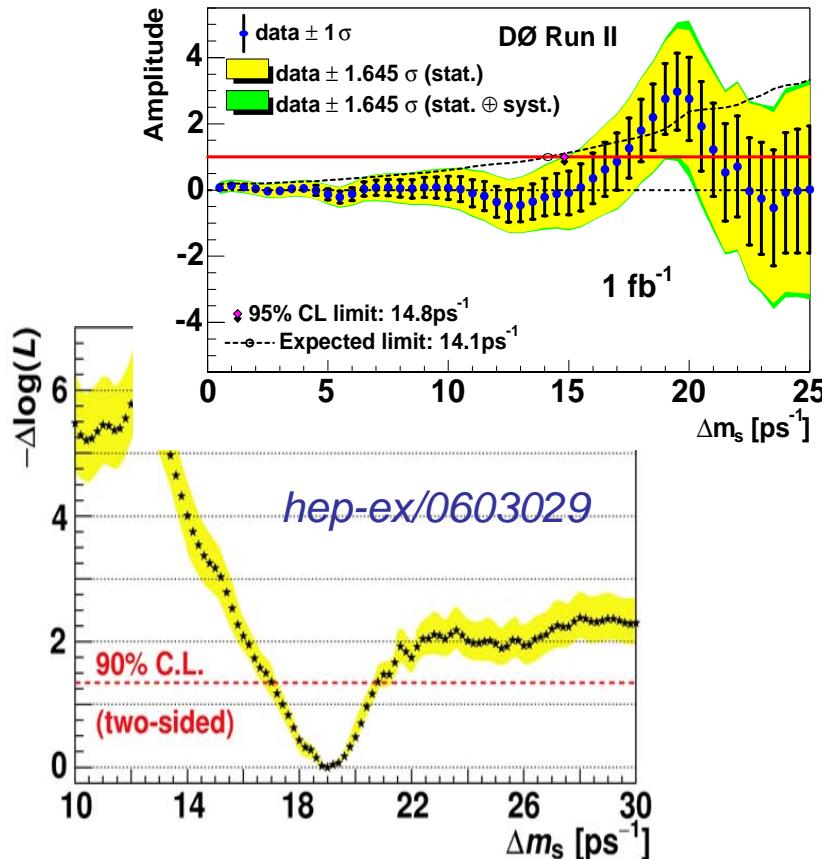


Events: 3,600 in hadronic mode
37,000 in leptonic mode

Oscillation Frequency

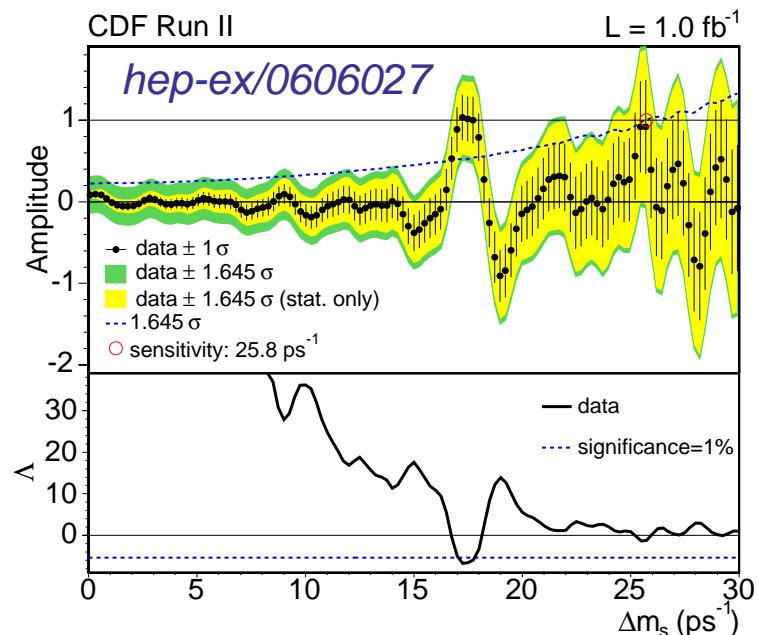
$$P^{\text{osc.}/\text{no-osc.}} = \frac{\Gamma}{2} e^{-\Gamma \cdot t} \cdot (1 \pm D \cdot \cos(\Delta m_s \cdot t) \cdot \mathcal{A})$$

$\mathcal{A}=1$: oscillation
 $\mathcal{A}=0$: no oscillation



$17 < \Delta m_s < 21 \text{ ps}^{-1}$ @ 90% CL

Deviation from $A=0$:
DØ: at 2.5 sigma
CDF: at 3.7 sigma



$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}$

Summary

- Many new results on masses, lifetimes and decay branching ratios of B hadrons from 1 fb^{-1} dataset.
- Sensitivities of rare decays are approaching Standard Model predictions, expected to observe some of them in Run II
- First measurement of B_s oscillation frequency. Golden opportunity for careful studies of B_s system.
- Too many interesting heavy flavor results from Tevatron, impossible to cover them all. People interested are suggested to visit CDF and DØ B physics web pages:
CDF: <http://www-cdf.fnal.gov/physics/new/bottom/bottom.html>
DØ: <http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm>
- New results from increasingly large datasets are expected over the next few years.